Final Report for AOARD Grant FA2386-10-1-4046 "**Enabling Lightwave Electronics with Nanotechnology: Synthesizing Attosecond Waveforms from Frequency Combs Generated in Ferroelectric Photonic Structures**"

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Abstract: The goal of this project is to demonstrate the synthesis of femtosecond to subfemtosecond time scale electric waveforms of arbitrary shape in a compact setting. We demonstrated in this project that periodic-poled photonic structures for cascaded multiharmonic generation can be reliably reproduced with our poling technique which exhibits the nanometer precision that the process requires. We have identified an ultrabroad band acousto-optic modulator (programmable dispersion filter) that is compact and will shrink the dimensions of our waveform generator by more than a factor of ten. We successfully tested this modulator and showed that it has good diffraction efficiency throughout the entire multioctave bandwidth of our light source and time synchronization for phase modulation has been accomplished. The remaining step in this project is to perform the waveform synthesis with these components to demonstrate a compact optical waveform synthesizer.

Introduction:

Function generators routinely produce electric fields in various shapes such as a sine wave, sawtooth, square, triangular and even sophisticated arbitrary waveforms in the RF regime. These function generators employ electronic oscillators whose speed is limited to <~100 GHz to obtain the waveforms. It is of great interest but has remained a major challenge to extend the production of similar waveforms to the optical region (10^{15} cycles per second) [1]. Up until now optical waveforms that have been synthesized are shaped envelopes that engulf many cycles of a rapidly oscillating electromagnetic field.[2] The challenge that has remained is the synthesis of the instantaneous electric field rather than the synthesis of the envelope of the electric field.

Optical waveforms generation and synthesis is an important and emerging research which affords the capacity to control the electronic behavior in attosecond time scale by an optical field analogous to controlling the current in nanosecond scale by a microwave field. We developed molecular modulation to generate an equidistant comb of frequencies that are harmonics of a fundamental input. By manipulating the phase and amplitude of five discrete harmonics spanning the blue to mid-infrared frequencies we succeeded to produce instantaneous optical fields in the shape of square, sawtooth, and sub-cycle sine and cosine pulses at a repetition rate of 125 THz [3]. In that experiment we developed an all-optical shaper-assisted linear cross correlation technique to retrieve these fields and thereby verified their shapes and confirmed the critical role of carrier-envelope phase in Fourier synthesis of optical waveforms. Yet comb generation and light manipulation require an apparatus that is space consuming and bulky.

It is the goal of this project to demonstrate the synthesis of femtosecond to subfemtosecond time scale electric waveforms of arbitrary shape in a compact setting: using multiple harmonics that are produced from a nonlinear photonic crystal consisting of periodic structures that required nanometer scale precision in its fabrication.

Experiment:

There are three major steps to achieve a compact optical waveform synthesizer. The first is the generation of a comb of harmonic frequencies. In previous work we fabricated a periodically-poled lithium tantalate (PPLT) crystal that has four poled periodic domains for cascaded quasi-phase-matched harmonic generation up to the fifth harmonic. The harmonics were generated in

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14. ABSTRACT
This is the report of a project to demonstrate the synthesis of femtosecond to subfemtosecond time scale electric waveforms of arbitrary shape in a compact setting.

15. SUBJECT TERMS
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consecutive segments of the crystal.(Fig. 1) Due to the sensitivity in phase-matching, the fabrication of this crystal requires nanometer precision in order to simultaneously satisfy the phase-matching condition for all four processes in generating the multiple harmonics in one single crystal [4]. For that experiment we designed and made a lithographic mask. With it we would be able to reproduce as many crystals of the same design as we desire. We used this mask and reproduced a second PPLT crystal exclusively for this project.

Fig. 1. Schematic of multiharmonic generation in a monolithic periodically poled crystal.

The second step is to set and control the amplitude and phase of the harmonics. In prior experiments we used liquid crystal spatial light modulators in a 4f prism optical arrangement for this purpose. The arrangement is commonly used in the ultrafast community. Due to the multi-octave bandwidth the 4f prism set up takes up a lot of table top space in order to allow enough separation between the harmonics when they pass through the modulators. In order to achieve compactness, a different approach is needed. Acousto-optic programmable dispersive filters (AOPDF) have been developed for optical signal processing, polarization switching in lasers, and pulse shaping of ultrafast lasers. These are compact devices that are based on the Acousto-optic modulation effect. The standard units have an optical bandwidth of only a few hundred nm. We worked with the supplier to modify the standard design to provide us an ultra-broad band AOPDF. The modification involves expanding the range of RF frequency which required a new transducer to couple the RF into the TiO_2 crystal where the acousto-optic modulation takes place. The unit was delivered to us near the end of 2010 and is under testing. Some of the test results are presented in the next section. Fig. 2 is a picture of the AOPDF. After mounting the unit takes up less than 10 x 15 cm^2 which is smaller by a factor of 10 of the 4f prism set up.

Fig. 2. Picture of an ultrabroad bandwidth programmable acousto-optic dispersive filter manufactured by Fastlite for amplitude and phase adjustment of the laser harmonics.

The AOPDF was designed to synchronize with MHz rep rate ultrafast lasers. Since our laser runs at a much lower rep rate it was necessary to separately develop an electronic circuit to synchronize the RF generator of the AOPDF to the pulses of our laser. This was successfully completed and the AOPDF can now be implemented into our optical system. Test results on amplitude and phase adjustments are reported below.

The final step is to measure the waveforms, using the shaper-assisted linear cross-correlation technique we developed for this purpose [5]. The procedure employs the same modulators as in the amplitude and phase adjustments above, and involves setting up an interferometric scheme for four of the five harmonic frequencies to obtain heterodyne signals that result from interference of the harmonics in a f-2f scheme. Since the strength of the harmonic output from the PPLT crystal is lower than those obtained from molecular modulation, we believe the heterodyne signals will be weaker to create a challenge when characterizing the waveforms.

Results and Discussion:

We first determined the operating characteristics of the PPLT crystal fabricated for use in this project. We determined the average output power at the fifth harmonic as a function of temperature and input wavelength. The result is shown in Fig. 3.

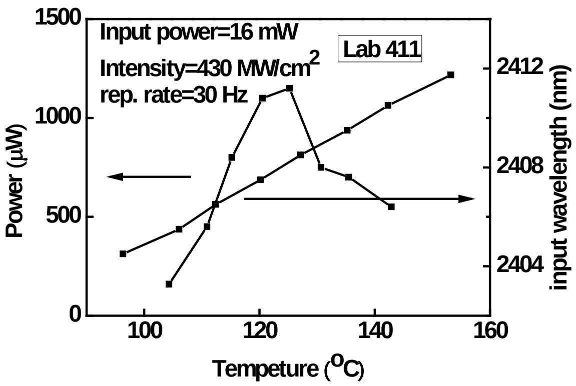


Fig. 3. Fifth harmonic power as a function of crystal temperature and input wavelength.

The input power was fixed at 16 mW. The highest 5^{th} harmonic output of 1.1 mW occurred at 2408.5 nm and 127^{o}C. For optimal operation we wish to have the highest 5^{th} harmonic power. Hence for the rest of this project we shall use 2408.5 nm as the input fundamental wavelength. For this input, we measured the power distribution of the five harmonics that were generated as a function of temperature. From the temperature dependence we may then choose the operating parameters for waveform synthesis.

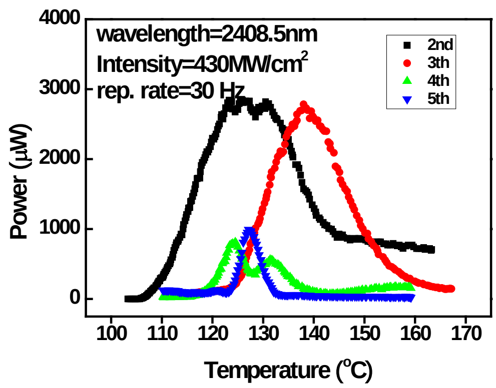
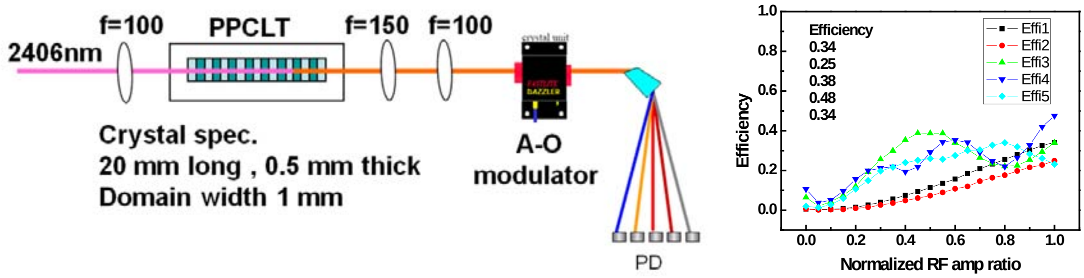


Fig. 4. Average power of the harmonics as a function of crystal temperature, input is 2408.5 nm.

The results in Fig. 4 indicate that we are able to extract all five harmonics from this crystal. The process of cascaded harmonics generation is viable since the crystal can be reproduced using our poling technique despite of the nanometer tolerance requirement. At 127^{o}C the fifth harmonic has the highest power at the expense of power depletion at the fourth harmonic. The fundamental is depleted also by nearly 50%. While the power distribution among the harmonics depends on the desired waveform, it is preferred that none of the harmonics is depleted by more than ~25% in order to maintain the fidelity of the waves. Given this criteria, a more superior temperature for waveform synthesis under these laser conditions would be ~130°C. A solution to reduce depletion of the input pump power is to shift the input wavelength to 2410 nm (see Fig. 3). We shall repeat the measurements at the new wavelength to determine if this is indeed feasible.

We have measured the operation of the ultrabroad band AOPDF. The specified single wavelength diffraction efficiency of the device is 80% and we are able to check that using the set up shown in Fig. 5. The efficiency drops when all five harmonics



are used because the total RF power

Fig. 5. Measurement of diffraction efficiency of the acousto-optic programmable diffraction filter: left, apparatus for the measurement; right, diffracted intensity of the harmonics as a function of normalized RF power.

that can be used in the diffraction is limited by the manufacturer to protect the RF transducer.

Consequently the net efficiency with all five harmonics incident simultaneously is lower. With optimal RF power ratio, the efficiency we measured was 34%, 25%, 38%, 48%, and 34%. We are satisfied with these numbers since it is a sacrifice of only a factor of two in exchange for the extended bandwidth for the modulator and its compactness. The measurements were performed at an input of 2406 nm, but similar results are expected at nearby wavelengths.

Phase measurements presented a problem initially. Our initial attempts to determine phase modulation failed. This is because the external trigger of the filter has an intrinsic jitter of ~3 ns. This leads to a 0.25π phase shift at the fourth harmonic wavelength and is too large to be acceptable. For proper phase adjustments, the timing of the phase of the RF power launched into the filter must be synchronized to that of the laser pulse. After getting a better understanding of the filter's electronics, we found that it is necessary to use the clock of the filter as the master trigger for all events in the experiment. Hence we designed and built a divider circuit using the 27 MHz clock from the filter for the purpose. With that the relative timing between the RF and our laser pulse is reduced to acceptable level. The evidence is from an interference measurement that we did. The apparatus is shown in Fig. 6 and the observed phase fringes are shown in Fig. 7. The test was done at 602 nm.

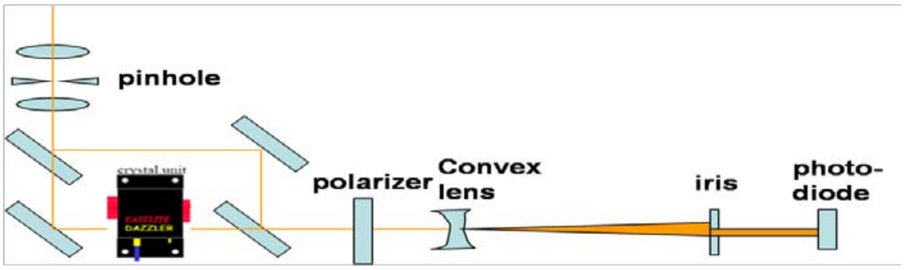


Fig. 6. Mach-Zender interferometer set up to measure phase modulation by AOPDF.

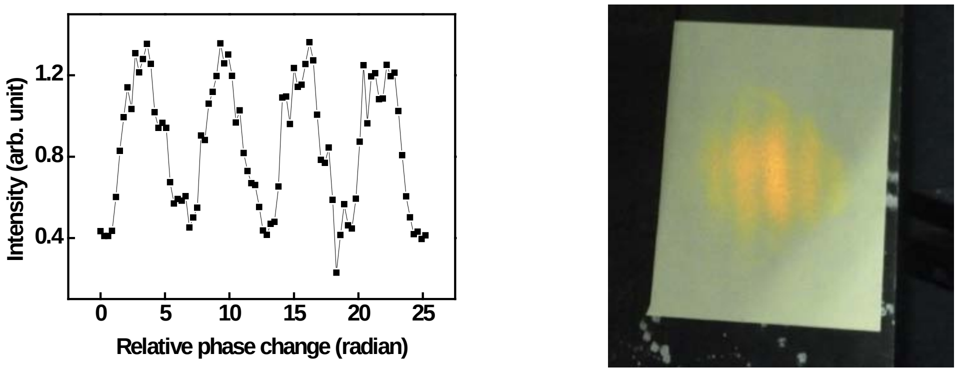


Fig. 7. Left: Interferometric fringes at 602 nm recorded when the RF delay of the AOPDF is adjusted. Right: picture showing the fringes at one delay setting.

Remaining work is to test the phase delays when all harmonics are incident into the AOPDF simultaneously. Once that is done to our satisfaction, then essentially all foreseeable obstacles are removed and the preparations completed to move forward to step three, which is to synthesize and characterize optical waveforms with this compact set up. We expect that this can be accomplished within the next few months.

The footprint of the ferroelectric photonic crystal multiharmonic generator and the acousto-optic programmable filter is small. Together with a compact single frequency laser source the entire system will be compact, and even portable. It is anticipated that this system can be developed into the optical analog of an electronic function generator with pulse trains in the femtosecond to subfemtosecond regime. Such a source can be useful for testing of nanoelectronic and nanophotonic devices and for full bandwidth optical communication.

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List of Publications: none so far.